WHAT IS CLAIMED IS:

1. A method for qualifying accuracy of a machining system having a multi-axis numerically controlled machine supporting a machine tool for performing a machining operation on a workpiece in a desired location thereof, the workpiece having a predetermined geometry, the method comprising:

identifying a plurality of quantifiable potential errors ϵ in the machine contributing toward inaccuracy in positioning of the machine tool on the workpiece;

deriving an equation for each error ϵ relating the magnitude of the machine tool position error ΔS caused by said error ϵ to the magnitude of said error ϵ and to the geometry of the workpiece;

statistically adding the plurality of position errors ΔS so as to determine a total position error ΔS_{Total};

establishing a maximum allowable value for the total position error ΔS_{Total}; and

determining a maximum allowable magnitude for each error ϵ such that, when all of the position errors ΔS are calculated based on said equations and the total error ΔS_{Total} is calculated by said statistical adding of the position errors ΔS, the calculated ΔS_{Total} is approximately equal to and not exceeding said maximum allowable value.

2. The method of claim 1, further comprising the steps, performed in between machining operations, of:

periodically measuring at least some of the errors ϵ in the machine positioning;

comparing each measured error ϵ with the maximum allowable magnitude of said error; and

if any measured error ϵ exceeds its maximum allowable magnitude, correcting the machine to bring said error ϵ within its maximum allowable magnitude before continuing with machining operations.

3. The method of claim 2, wherein the step of measuring errors in machine positioning comprises using an independent position-detecting system to check accuracy of positioning of the machine at a plurality of locations spaced apart in a

working envelope of the machine, the position-detecting system comprising a target mounted adjacent a spindle of the machine operable for holding the machine tool and a measuring instrument operable to measure coordinates of the target, wherein the machine is moved so as to position the spindle at each of said plurality of locations and the coordinates of the target are measured by the position-detecting system for each location and errors in positioning of the machine are determined by comparing the measured coordinates with expected values.

4. The method of claim 3, wherein the machine is movable within the working envelope along each of at least two orthogonal translational axes, and further comprising creating a master frame of reference relative to the translational axes of the machine before checking the accuracy of the machine at each of the locations about the working envelope, the master frame of reference being created by:

moving the machine along a first of the translational axes and using the measuring instrument to determine the coordinates of the target at each of a plurality of spaced-apart points along the first translational axis;

moving the machine along a second of the translational axes orthogonal to the first translational axis and using the measuring instrument to determine the coordinates of the target at each of a plurality of spaced-apart points along the second translational axis; and

calculating a linear fit of the determined coordinates so as to create a set of mutually orthogonal axes defining the master frame of reference, and wherein the master frame of reference is used during the checking of the positioning accuracy of the machine.

5. A method of qualifying the accuracy of a machining system having a multi-axis numerically controlled machine and a flexible holding fixture for holding workpieces to be machined and proceeding to machining operations upon qualification, the method comprising:

mounting a contact measuring probe in a spindle of the machine where a machine tool would ordinarily be mounted for machining, and checking positioning accuracy of the machine by moving the machine to cause the probe to contact a fixed monument mounted in a known position such that the probe measures a position of

the monument, and proceeding to the next step only if the probe-measured position of the monument is within a predetermined tolerance of the known position;

subsequently checking positioning accuracy of the holding fixture by moving the machine to cause the probe to contact each of a plurality of holding members of the fixture that have been placed in positions determined within a numerical control unit of the holding fixture that controls positioning of the holding members, such that the probe measures a position of each holding member; and

proceeding to machining operations only if the probe-measured position of each holding member that was checked is within a predetermined tolerance of the position determined within the numerical control unit of the holding fixture.

6. The method of claim 5, further comprising globally checking positioning accuracy of the machine throughout a working envelope thereof by:

mounting a reflective target on the machine adjacent the spindle;

mounting a laser measuring instrument in a fixed location proximate the machine;

moving the machine such that the target is placed in each of a plurality of positions spaced apart throughout the working envelope;

directing a laser beam from the laser measuring instrument so as to be reflected from the target back to the laser measuring instrument, the laser measuring instrument being operable to calculate position coordinates of the target based on characteristics derived from the reflected beam, whereby the position coordinates of the target are determined for each position in the working envelope; and

proceeding to subsequent operations only if the position coordinates of the target determined in the laser measuring instrument for each position of the target are within predetermined tolerances of position coordinates determined within a numerical control unit of the machine.

7. The method of claim 6, wherein the machine is movable along each of at least first and second translational axes that are perpendicular, and wherein a master frame of reference based on the machine's translational axes is created in the laser measuring instrument prior to the global accuracy check of the machine, by:

moving the machine along the first translational axis and using the measuring

instrument to determine the coordinates of the target at each of a plurality of spaced-apart points along the first translational axis;

moving the machine along the second translational axis and using the measuring instrument to determine the coordinates of the target at each of a plurality of spaced-apart points along the second translational axis; and

calculating a linear fit of the determined coordinates so as to create a set of mutually orthogonal axes defining the master frame of reference;

and wherein the coordinates of the target are determined in the master frame of reference during the global accuracy check of the machine.

8. The method of claim 7, wherein the machine includes a wrist formed by a head and a spindle-holding body, the head being rotatably mounted on a ram that is translatable independently along each of three mutually orthogonal X, Y, and Z axes, the head being rotatable on the ram about a first rotational axis that is nominally parallel to the Z axis, the spindle-holding body being rotatable on the head about a second rotational axis perpendicular to the first rotational axis, the spindle being mounted on the spindle-holding body such that when the head and body are each rotated to home positions thereof an axis of the spindle is nominally aligned along the first rotational axis, and wherein the step of mounting the contact measuring probe comprises mounting the probe in the spindle such that the probe extends lengthwise along and aligned with the axis of the spindle.

9. The method of claim 8, further comprising checking accuracy and alignment of the second rotational axis by placing the spindle-holding body in its home position and rotating the head about the first rotational axis to each of two angularly spaced-apart positions, and detecting whether the probe moves from its position in space as a result of the rotation of the head.

10. The method of claim 8, wherein the mounting of the probe in the spindle is performed such that the probe has a predetermined length measured along the axis of the spindle from a tip of the probe to the second rotational axis.

11. The method of claim 10, wherein the length from the tip of the probe to the second rotational axis is checked to ensure that it is within a predetermined

tolerance of the predetermined length prior to checking the positioning accuracy of the machine and the holding fixture with the probe.

12. The method of claim 11, wherein the spindle is translatable along its axis relative to the spindle-holding body toward and away from the second rotational axis about which the spindle-holding body rotates, and wherein the spindle is translated to a home position thereof prior to checking the length of the probe.

13. A method for assessing accuracy of positioning of a multi-axis numerically controlled machine, the machine being of the type having a tool-holding spindle mounted on a ram that is movable along each of at least two mutually orthogonal translational axes, the machine having a numerical control unit for controlling positioning of the spindle, the method comprising:

mounting a target on the machine adjacent the spindle and mounting a measuring instrument in a fixed position proximate the machine, the measuring instrument being operable to measure position coordinates of the target;

creating a master frame of reference relative to the translational axes of the machine by:

moving the machine along a first of the translational axes and using the measuring instrument to determine the coordinates of the target at each of a plurality of spaced-apart points along the first translational axis;

moving the machine along a second of the translational axes orthogonal to the first translational axis and using the measuring instrument to determine the coordinates of the target at each of a plurality of spaced-apart points along the second translational axis; and

calculating a linear fit of the determined coordinates so as to create a set of mutually orthogonal axes defining the master frame of reference; and

checking accuracy of positioning of the machine in the master frame of reference by moving the machine so as to position the spindle at each of a plurality of locations, measuring the coordinates of the target in the measuring instrument for each said location, and determining errors in positioning of the machine by comparing the measured coordinates with machine-determined coordinates determined within the numerical control unit of the machine.

14. The method of claim 13, wherein the method is adapted to check accuracy of positioning of a numerically controlled holding fixture used in conjunction with the machine for holding a workpiece to be machined, the fixture having a plurality of numerically controlled, movable holding members operable to engage the workpiece, the method further comprising:

placing each of a plurality of the holding members of the fixture in a fixed position;

mounting a measuring probe in the spindle of the machine, the probe being operable to cause the machine to determine a position of an object when the probe contacts the object;

moving the machine to each of said plurality of the holding members such that the probe contacts the holding member and the machine determines a position of the holding member along at least one axis of the master frame of reference;

causing the fixture to internally determine a position of each holding member that is probed by the machine; and

comparing the machine-determined position of each of said plurality of the holding members with the position of the holding member determined within the holding fixture.

15. The method of claim 14, further comprising calibrating the holding fixture by applying software corrections within a numerical control unit of the holding fixture so as to compensate for differences between the machine-determined position and the fixture-determined position of one or more of the holding members.

16. The method of claim 15, further comprising performing a post-calibration check of the holding fixture by placing each of a plurality of the holding members in a plurality of fixed positions and moving the machine such that the probe contacts the holding member in each of the fixed positions, and comparing a machine-determined position of the holding member with a fixture-determined position of the holding member for each of the fixed positions.

17. The method of claim 16, further comprising making hardware adjustments to at least one of the holding fixture and the machine when a difference between the

machine-determined position and the fixture-determined position of one or more of the holding members determined during the post-calibration check exceeds a maximum allowable difference.

18. The method of claim 13, further comprising:

causing the machine to move along a predetermined path such that the target is moved along an actual path in space;

measuring the position of the target with the measuring instrument as the machine moves the target along the actual path such that the actual position of the target is determined at a plurality of points along the actual path; and

calculating a deviation between the actual position of the target at each point and an intended position corresponding to the predetermined path.

19. The method of claim 18, wherein the machine is operable to move the spindle independently along each of three mutually orthogonal X, Y, and Z axes, and wherein the machine is programmed to move along a predetermined path in each of XY, XZ, and YZ planes such that the target traverses an actual path nominally located in each plane, and the measuring instrument is used to track the target along each of the actual paths and deviations between actual positions and intended positions of the target are calculated at points along each path.

20. A method for assessing accuracy of positioning of a multi-axis numerically controlled machine and for diagnosing and correcting sources of errors in positioning, the machine being of the type having a tool-holding spindle mounted on a spindle-holding body, the body being rotatably mounted in a head which is rotatably mounted on a ram that is movable along each of three mutually orthogonal translational axes, the method comprising:

(a) mounting a measuring probe in the spindle such that, when the body is in a home position thereof, a longitudinal axis of the probe is colinearly aligned with a first rotational axis of the machine about which the head rotates with respect to the ram, and such that the probe has a predetermined length between a tip of the probe and a second rotational axis about which the body rotates with respect to the head;

(b) checking accuracy of the machine along each of the three translational axes by placing the body and head in fixed rotational positions, causing the machine to move the ram along each of the three translational axes such that the probe tip is brought into contact with a fixed monument, comparing positions of the monument measured by the probe with previously taught positions so as to determine whether there is a shift of the machine or the monument along any of the three translational axes, and correcting any such shift that exceeds a maximum allowable shift; and

(c) checking accuracy of rotational positioning of the body of the machine by positioning the head in a position in which the second rotational axis is parallel with one of the translational axes, rotating the body about the second rotational axis and detecting whether the tip of the probe undergoes movement along said one translational axis, said movement indicating inaccuracy in rotational positioning of the head, and correcting any such inaccuracy in rotational positioning that exceeds a maximum allowable inaccuracy.

21. The method of claim 20, wherein mounting the measuring probe comprises:

mounting the measuring probe in the tool-holding spindle of the machine such that the longitudinal axis of the probe is generally aligned along an axis of the spindle, and ensuring accuracy of alignment and length of the probe by performing the steps of:

(1) checking alignment of the probe with the first rotational axis of the machine about which the head is rotatable by positioning the body in a position in which the axis of the probe is supposed to be aligned with the first rotational axis, rotating the head about the first rotational axis and detecting whether the tip of the probe deviates from a fixed position in space as a result of the rotation, such deviation indicating misalignment of the probe with the first rotational axis, and correcting any such misalignment that exceeds a maximum allowable misalignment; and

(2) determining a length from the tip of the probe to the second rotational axis about which the body rotates in the head, and adjusting the

length to within a tolerance of a desired length.

22. The method of claim 21, wherein step (1) comprises rotating the head about the first rotational axis to a first position and moving the machine to cause the probe tip to contact a fixed monument such that a first set of position coordinates for the monument is measured by the machine, then rotating the head about the first rotational axis to a second position and again moving the machine to cause the probe tip to contact the monument such that a second set of position coordinates for the monument is measured by the machine, and comparing the first and second sets of position coordinates to determine whether there is misalignment of the probe relative to the first rotational axis.

23. The method of claim 21, wherein step (2) comprises positioning the machine such that the probe is parallel with a first of the translational axes of the machine, moving the machine along the first translational axis until the tip of the probe contacts one side of a fixed monument such that the machine measures a position of said one side along the first translational axis, then rotating the body 180 degrees about the second rotational axis and moving the machine along the first translational axis until the tip of the probe contacts an opposite side of the fixed monument such that the machine measures a position of said opposite side along the first translational axis, and calculating the length from the probe tip to the second rotational axis based on the measured positions of the two sides of the monument and a known distance between the two sides.

24. The method of claim 20, further comprising using an independent position-detecting system to check accuracy of positioning of the machine at a plurality of locations spaced apart in a working envelope of the machine, the position-detecting system comprising a target mounted adjacent the spindle and a measuring instrument operable to measure coordinates of the target, wherein the machine is moved so as to position the spindle at each of said plurality of locations and the coordinates of the target are measured by the position-detecting system for each location and errors in positioning of the machine are determined by comparing the measured coordinates with expected values.

25. The method of claim 24, further comprising creating a master frame of reference relative to the translational axes of the machine before checking the accuracy of the machine at each of the locations about the working envelope, the master frame of reference being created by:

moving the machine along a first of the translational axes and using the measuring instrument to determine the coordinates of the target at each of a plurality of spaced-apart points along the first translational axis;

moving the machine along a second of the translational axes orthogonal to the first translational axis and using the measuring instrument to determine the coordinates of the target at each of a plurality of spaced-apart points along the second translational axis; and

calculating a linear fit of the determined coordinates so as to create a set of mutually orthogonal axes defining the master frame of reference, and wherein the master frame of reference is used during the checking of the positioning accuracy of the machine.

26. The method of claim 25, further comprising checking accuracy of rotational positioning of the machine about the first and second rotational axes by placing the ram in a fixed position and rotating the body and the head so as to position the target at a plurality of spaced-apart points, and using the measuring instrument to determine coordinates of the target at each of the points based on the master frame of reference, and comparing the determined coordinates with expected values.

27. The method of claim 25, wherein the method is adapted to check accuracy of positioning of a numerically controlled workpiece holding fixture used in conjunction with the machine for holding a workpiece to be machined, the fixture having a plurality of numerically controlled, movable holding members operable to engage the workpiece, the method further comprising:

placing the holding members of the fixture in fixed positions;

moving the machine to each of a plurality of the holding members such that the probe contacts each holding member and the machine determines a position of the holding member along at least one axis of the master frame of reference; and

comparing the machine-determined position of each holding member with a

position of the holding member determined within the holding fixture.

28. The method of claim 27, further comprising:

applying corrective measures to the holding fixture when a difference between the machine-determined position and the fixture-determined position of one or more of the holding members exceeds a maximum allowable difference.

29. The method of claim 28, wherein applying corrective measures comprises applying one or more correction factors within a numerical control unit of the holding fixture based on said difference between the machine-determined position and the fixture-determined position of each holding member.

30. The method of claim 29, wherein the holding members are movable along each of at least first and second axes of the fixture generally aligned with first and second axes of the master frame of reference, the probe contacting each holding member at two or more surfaces such that the machine determines the position of the holding member along each of the first and second axes of the master frame of reference and the fixture determines the position of the holding member along each of the first and second axes of the fixture, and wherein correction factors are applied within the numerical control unit of the fixture for correcting positioning of the holding members along each of the axes of the fixture.

31. The method of claim 27, wherein the machine includes a prime mover mounted on linear ways defining the first translational axis of the machine, the ram is slidable on the prime mover along linear ways defining the second translational axis of the machine and along linear ways defining a third translational axis of the machine, and the holding members of the fixture comprise vacuum cups mounted on rods, each rod being extendable and retractable along a direction generally parallel with the third translational axis of the machine, and wherein a plurality of the rods are placed at a constant fixture-determined position along the third translational axis while the probe is used to determine a machine-determined position along the third translational axis for said plurality of the rods, and corrective actions are applied to the fixture if the machine-determined positions of the rods along the third translational axis differ from the fixture-determined positions by more than maximum allowable

amounts.

32. A method for assessing accuracy of positioning of a multi-axis numerically controlled machine and of a holding fixture used in conjunction with the machine for holding a workpiece for machining, the machine being of the type having a tool-holding spindle mounted on a ram that is movable on ways along each of three mutually orthogonal translational axes, the fixture being of the type having a plurality of movable holding members variably positionable along at least one direction for engaging the workpiece and having a numerical control unit operable to control positioning of the holding members and to internally determine a position of each holding member along said at least one direction, the method comprising:

mounting a measuring probe in the spindle of the machine, the probe being operable to cause the machine to determine a position of a tip of the probe relative to a frame of reference of the machine when the tip makes contact with an object;

placing each of a plurality of the holding members of the fixture in a fixed position along said at least one direction in which the holding members are movable, the numerical control unit of the holding fixture determining a position of each holding member along said at least one direction;

moving the machine to each of said plurality of the holding members such that the probe tip contacts the holding member and the machine determines a position of the holding member along at least one axis of the machine's frame of reference; and

comparing the machine-determined position of each holding member with a position of the holding member determined within the holding fixture.

33. The method of claim 32, further comprising:

applying corrective measures to the holding fixture when a difference between the machine-determined position and the fixture-determined position of one or more of the holding members exceeds a maximum allowable difference.

34. The method of claim 33, wherein one or more correction factors are applied within the numerical control unit of the holding fixture based on said difference between the machine-determined position and the fixture-determined position of each holding member.

35. A method of detecting and diagnosing potential sources of errors in positioning of a machining system having a multi-axis numerically controlled machine and a flexible holding fixture for holding workpieces to be machined, the machine having a tool-holding spindle mounted on a wrist of the machine that has two rotatable joints defining two perpendicular rotation axes, the machine including linear ways permitting the wrist to be translated along each of at least two mutually orthogonal translation axes, the holding fixture having a plurality of holding members that are movable relative to the machine and having a control unit operable to control positioning of the holding members, the method comprising:

(a) performing a probe check to assess accuracy in positioning of the machine along each of the translation axes by:

mounting a measuring probe in the spindle such that a longitudinal axis of the probe has a predetermined orientation with respect to the rotation axes of the machine, the probe being operable to cause the machine to determine a position of a tip of the probe when the tip contacts an object;

moving the machine along each translation axis while the other translation axes and the rotation axes are fixed so as to cause the probe tip to contact a corresponding fixed reference surface defined for each translation axis such that the machine determines a position of the reference surface;

determining a difference between the machine-determined position of each reference surface and a previously taught position for the reference surface; and

when any of the differences exceeds a maximum allowable difference, checking each of a plurality of possible causes that include shifting of the reference surface and shifting of the machine along the translation axes, and correcting any such shift that is unacceptably large; and

(b) performing a probe check of the holding fixture to assess accuracy in positioning of the holding members by:

causing the holding fixture to position at least some of the holding members such that a predefined surface of each said holding member is located in a predetermined position along one of the translation axes of the machine as determined within the control unit of the fixture;

moving the machine along said one translation axis while the other translation axes and the rotation axes are fixed so as to cause the probe tip to contact said predefined surface of each of a plurality of the holding members such that the machine determines a position of said predefined surface along said one translation axis;

calculating a discrepancy between the machine-determined position of said predefined surface and the position determined within the control unit of the fixture for each holding member contacted by the probe; and

accounting for the discrepancies within the control unit of the fixture such that the control unit adjusts the positioning of the holding members by amounts corresponding to the discrepancies.

36. The method of claim 35, wherein the procedures defined in steps (a) and (b) are each performed on a periodic basis in between machining operations on workpieces.

37. The method of claim 36, wherein the procedure defined in step (a) is performed more frequently than the procedure defined in step (b).

38. The method of claim 35, further comprising performing a post-calibration probe check of the holding fixture after the procedure defined in step (b), the post-calibration probe check comprising repeating step (b) with at least some of the holding members each being positioned in at least one position different from the position used in step (b).

39. The method of claim 37, further comprising applying physical corrections to the holding fixture if the discrepancies between the machine-determined position and the fixture-determined position of the holding members calculated during the post-calibration probe check exceed maximum allowable values.

40. The method of claim 39, further comprising providing a position-detecting system having a target mounted on the machine wrist adjacent the spindle and a measuring instrument operable to measure coordinates of the target, and performing a global positioning accuracy check of the machine by moving the

machine so as to position the spindle at each of a plurality of locations spaced apart in a working envelope of the machine, using the measuring instrument to measure the coordinates of the target with the machine at each location, and calculating errors in positioning of the machine based on comparisons of the measured coordinates with expected values.

41. The method of claim 40, wherein the global positioning accuracy check further includes creating a master frame of reference relative to the translational axes of the machine before checking the accuracy of the machine at each of the locations about the working envelope, the master frame of reference being created by:

moving the machine along a first of the translational axes and using the measuring instrument to determine the coordinates of the target at each of a plurality of spaced-apart points along the first translational axis;

moving the machine along a second of the translational axes orthogonal to the first translational axis and using the measuring instrument to determine the coordinates of the target at each of a plurality of spaced-apart points along the second translational axis; and

calculating a linear fit of the determined coordinates so as to create a set of mutually orthogonal axes defining the master frame of reference, and wherein the master frame of reference is used during the checking of the positioning accuracy of the machine.

42. The method of claim 40, wherein the global positioning accuracy check is performed on a periodic basis with less frequency than the procedures defined in steps (a) and (b).